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MIXING OF MULTIPLE DILUTION JETS WITH A HOT PRIMARY AIRSTREAM FOR GAS TURBINE COMBUSTORS

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MIXING OF MULTIPLE DILUTION JETS WITH A HOT PRIMARY AIRSTREAM FOR GAS TURBINE COMBUSTORS

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Abstract

The mixing of multiple air jets with a subsonic heated crossflow in a constant area duct was studied experimentally. The jet-to-mainstream momentum flux ratio was varied from 6 to 60. Temperature and pressure surveys were made at several downstream locations for orifice geometries with parametric variation of orifice size and spacing. A mixing efficiency parameter was defined which characterized the effectiveness of the mixing over the range of conditions examined. It was found that for a given momentum flux ratio, there exists a ratio of orifice spacing to duct height which provides the best mixing.

Introduction

The objective of this study was to determine the penetration and mixing characteristics of multiple jets of cooling air injected normally into a heated crossflow in a constant area duct. The study was motivated by considerations of dilution zone mixing in gas turbine combustion chambers. For this application, rapid mixing of the diluent air with the high temperature combustion gases leaving the primary zone is desired to (1) provide a rapid quench for any ongoing chemical reactions, (2) provide a suitable temperature distribution at the turbine inlet, and (3) reduce combustor length.

Recent experimental investigations[1,2] have provided detailed velocity and temperature field measurements downstream of a heated jet injected into an ambient temperature crossflow. Using the experimental data from these studies, a correlation method for approximating the temperature distribution in the plane of symmetry downstream of a single jet injected into a crossflow was developed.[3]

The studies of single jets in an unbounded crossflow provide no information on the effects of multiple jet interaction or of jet interaction with an opposite wall. Also since the injection of a single jet cannot alter the mean temperature of an unbounded crossflow, information relevant to the combustor exit conditions such as the average temperature and the local deviations from the average are not available from single jet results. In addition, the results of references 1 and 2 or the correlations of reference 3 must be applied deductively to the cooling problem since the jets were heated.

It was because of these limitations of the extant single jet data that the present investigation was undertaken. The range of geometric and flow variables for this study were selected to make the experimental data relevant to the design of combustors for gas turbine engines. The results are presented in terms of the jet-to-mainstream momentum flux ratio and the dimensionless orifice size and orifice spacing. The experiments were performed by the Aerojet Liquid Rocket Company under NASA Contract NAS3-15703.

Experimental Considerations

A schematic of the multiple jet flow field with the principal flow and geometric variables identified appears in Figure 1. The test section was 30.48 cm wide by 10.16 cm high. For all of the test results shown in this paper the nominal mainstream conditions were: velocity, U_∞ = 15 m/sec; temperature, T_∞ = 600 K. The jet velocity, V_j, was varied from 25 m/sec to 85 m/sec with the jets at ambient temperature, T_j = 300 K. The jets entered the test section through sharp-edged orifices in the plate separating the main duct from the secondary air plenum chamber. The orifice discharge coefficients varied from 0.66 at the lowest jet-to-mainstream velocity ratio to 0.62 at the highest velocity ratio.

The test conditions were established with the jet-to-mainstream momentum flux ratio, $J = (\rho_j V_j^2)/(\rho_\infty U_\infty^2)$, and the jet-to-mainstream density ratio, ρ_j/ρ_∞, as the primary independent flow variables. Momentum flux ratios investigated ranged from 6 to 60, with density ratios varied from 1.5 to 2.5. The symbols and parameters referenced in this paper are given in the appendix.

The primary independent geometric variables were the orifice size and the spacing between adjacent orifices. These were expressed in dimensionless form as the ratio of the duct height to the orifice diameter, H/D, and the ratio of the orifice spacing to the orifice diameter, S/D. Although the experiments were performed with S/D and H/D as the independent geometric variables, the ratio of these, S/H, may be considered as an independent variable in the place of either S/D or H/D. The orifice area may be expressed in dimensionless form as $A_j/A_\infty = (\pi/4)/[(H/D)(S/D)]$ which is the orifice-to-mainstream area ratio.

Because the objective of the study was to identify orifice configurations appropriate for optimum mixing within a minimum combustor length, the downstream stations surveyed were defined in terms of the duct height, H. Measurements of total pressure and temperature were made at 20 vertical and 21 horizontal positions in each of five planes at downstream locations from X/H = 0.25 to X/H = 2.0. The total span of the 21 horizontal positions was varied to correspond to twice the orifice spacing for each plate. This distance varied from 2.54 cm for the smallest orifice spacing to 20.32 cm for the largest spacing.

The experimental results for the temperature field are presented as three-dimensional profile plots of the dimensionless temperature difference ratio, θ, at each axial station. This parameter is defined by

$$\theta = \frac{T_\infty - T_i}{T_\infty - T_j} \qquad (1)$$

where T_i is the local temperature, T_∞ is the temperature of the undisturbed mainstream flow, and T_j is the jet temperature. Because $T_\infty > T_j$ the largest values of θ in any distribution correspond to the coolest regions of the flow. Additional aspects of the experimental program and the facility used are discussed in Reference 4.

Results and Discussion

In the following paragraphs data will be shown for several of the single row orifice plate configurations tested. These geometries appear to scale in Figure 2 with orifices shown for one-third of the width of the test duct.

Because of the volume of data obtained, a parameter was sought which would be sensitive to the degree of mixing as observed from the profile plots. Traditional measures, such as the pattern factor, were examined but did not provide a suitable measure of the mixing achieved with respect to the mixing attempted. A mixing efficiency parameter, E_T, was formulated which did provide adequate sensitivity to the mixing observed in the temperature distributions. This parameter may be expressed as

$$E_T = 100 \sum_{i=1}^{n} \left[\frac{\dot{W}_{ji}(T_i - T_j)}{\dot{W}_T(T_{EB} - T_j)} + \frac{\dot{W}_{\infty i}(T_i - T_\infty)}{\dot{W}_T(T_{EB} - T_j)} \right] \quad (2)$$

where T_{EB} is the ideal exit temperature calculated from the enthalpy balance, $\dot{W}_T$ is the total msss flow rate, and $W_{ji} + W_{\infty i} = W_i$ is the incremental mass flow rate at location i.

The application of Equation (2) requires a determination of the contribution of the primary (mainstream) and secondary (jet) flows to the local mass flux. This is accomplished by assuming that if the incremental temperature is less than the enthalpy balance temperature, the incremental flow is due to the secondary flow; i.e., if $T_i < T_{EB}$, then $W_{ji} = W_i$ and $W_{\infty i} = 0$. Similarly, if the temperature is greater than the enthalpy balance temperature, the flow is due to the primary flow; i.e., if $T_i > T_{EB}$ then $W_{\infty i} = W_i$ and $W_{ji} = 0$.

Effect of Flow Variables

The jet-to-mainstream momentum flux ratio, $J = (\rho_j V_j^2)/(\rho_\infty U_\infty^2)$, was found to be the most important operating variable influencing the mixing. The magnitude of this influence can be seen in temperature profile data at momentum flux ratios of 6 and 62 shown in Figure 3. Profile data are shown at downstream distances from $X/H = 0.25$ to $X/H = 2.0$ for an orifice plate with $S/D = 4$ and $H/D = 8$. The mixing efficiencies corresponding to each axial station show that the mixing is more efficient for the high momentum flux ratio than for the low momentum flux ratio. Note that the ratio of jet flow to mainstream flow, $\dot{W}_j/\dot{W}_\infty$, is approximately three times greater for the high momentum flux ratio than for the low momentum flux ratio. From these data and other results from Reference 4 not presented here it appears that the criteria for effective mixing are (1) jet penetration to approximately 1/2 the duct height within 2 jet diameters downstream, and (2) the establishment of a nearly symmetrical vertical temperature distribution about the centerline at this point. If these conditions are met, the temperature distribution will rapidly decay and spread toward a uniform distribution with increasing downstream distance.

Experiments performed with the density ratio varied from 1.5 to 2.5 at constant momentum ratios showed no significant change in the profiles or the mixing efficiencies with changing density ratios. Thus, the density ratio does not need to be considered independently from the momentum flux ratio at least for the ranges of these variables examined in this study.

Effect of Geometric Variables

The momentum flux ratio, and the density ratio are dependent on the combustor design conditions, e.g., inlet temperature and pressure, reference velocity, pressure drop, and fuel-air ratio. Thus for a given combustor, the dilution zone design parameters which may be varied to influence the combustor exit temperature distribution are the orifice diameter, orifice spacing, and orifice shape. However, since the flow conditions for a given combustor determine the required orifice area, the orifice size and spacing must be correctly coupled. In Figure 4, temperature profile data at $X/H = 1$ for momentum flux ratios of 6 and 60 are shown for three orifice configurations all having orifice-to-mainstream area ratios of 0.049. The differences in the profiles are evident, indicating that for a given operating condition considerable variations in the downstream temperature distributions can be effected by changes in the orifice diameter and spacing. This is consistent with the result of Reference 5, where fewer large orifices were found to provide better jet penetration than a larger number of small orifices for the same orifice area. In the following paragraphs, the effects of parametric variation of the geometric variables at a constant momentum flux ratio of $J = 25$ are discussed.

Effect of orifice spacing at constant diameter (constant J and H/D, variable S/D). For a given jet diameter and momentum flux ratio the uniformity in the vertical temperature distribution is increased with increased spacing as shown in Figure 5 by the temperature profiles for momentum flux ratio $J = 25$. These data are at $X/H = 1.0$ for four orifice plates with $H/D = 8$. The mixing efficiencies indicate a significant improvement in the mixing with S/D increased from 2 to 4. A further increase in S/D increases the vertical uniformity, but with attendant increase in the horizontal nonuniformity; the result is that the mixing efficiency does not increase for $S/D > 4$.

Effect of orifice diameter at constant S/D (constant J and S/D, variable H/D). For a given S/D and momentum flux ratio the jet penetration is increased significantly with increasing orifice diameter as shown by the profile data in Figure 6 for four orifice plate configurations with $S/D = 2$. These data are at $X/H = 1.0$ with $J = 25$. The mixing efficiency values for these tests show a monotonic increase from a low value of $E_T = 47$ for the smallest orifices, $H/D = 16$, to a high value of 85 for the largest orifices, $H/D = 4$. It should be noted that as orifice size increases at constant S/D, the ratio of dilution air to mainstream air increases; thus more efficient mixing of the hot mainstream and cool jets

occurs as more cooling is attempted.

Effect of orifice diameter at constant spacing (constant J and S/H, variable H/D. For a constant S/H (constant spacing) and momentum flux ratio, the effect of increasing orifice diameter is to shift the temperature distributions to higher θ values consistent with the larger dilution airflow without altering the shape of the distributions. This effect is shown in the temperature distributions in Figure 7 for three orifice configurations with constant spacing but with orifice-to-mainstream area ratios from 0.0245 to 0.098. The mixing efficiencies indicated for each profile plot also reflect the similarity in the distributions.

This is perhaps the most significant result of the present investigation since it suggests that for a given momentum ratio there exists a value of S/H for which the most efficient mixing occurs independent of orifice diameter. The orifice size can then be selected to provide the desired jet-to-mainstream mass flow split.

From the data shown, Figures 4 to 7, it appears that an S/H of 0.5 provides the best mixing for momentum flux ratios near J = 25. For smaller momentum ratios, the mixing is improved by increasing S/H to 1.0. For the lowest momentum flux ratio investigated, J = 6, the best E_T obtained within a downstream distance of two duct heights was 72, for S/H = 1; whereas for J = 24, E_T values of 92 were obtained within a downstream distance of two duct heights for S/H = 0.5. Thus for lower momentum flux ratios a greater downstream distance would be required to achieve a desired mixing efficiency than is required for higher momentum flux ratios.

For S/H = 0.5, at X/H = 2.0, the E_T values for J = 60 were nearly equal to those for J = 24 even though the profile data indicated overpenetration at J = 60. For S/H = 0.33, at X/H = 2.0, the highest E_T value obtained was for J = 60. The E_T value for J = 24 was 10% less than for J = 60, with the profile data indicating underpenetration at J = 24. From these results it appears that if the optimum cannot be attained, better mixing is achieved with overpenetration than with underpenetration.

Summary of Results

An experimental study was conducted to characterize the secondary air admission and mixing process for gas turbine combustors. This was accomplished by determining empirically the penetration and mixing characteristics of multiple jets of ambient temperature air injected normal to a heated mainstream flow.

Primary independent test variables were the orifice plate configurations and the jet-to-mainstream momentum flux ratio. The orifice plates contained sharp-edged orifices, with orifice diameters from 1/16 to 1/4 of the test section height tested. Center-to-center orifice spacings of from 2 to 6 times the orifice diameter were evaluated. All of the tests reported in this paper were conducted with a mainstream velocity of 15 m/sec at a mainstream temperature of 600 K. The jet-to-mainstream momentum flux ratio was varied from 6 to 60 by changing the jet velocity.

The principal results from this investigation were as follows:

1. A mixing efficiency parameter was defined which characterizes the effectiveness of the mixing over the range of operating and geometric conditions examined.

2. The jet-to-mainstream momentum flux ratio was the most important operating variable influencing jet penetration and mixing. The mixing efficiency was found to increase with increasing momentum flux ratio. Experiments performed with the density ratio varied at constant momentum flux ratios showed no significant change in the temperature profiles or the mixing efficiencies with changing density ratios.

3. For a given orifice diameter, the uniformity in the vertical temperature distribution was improved by increasing the spacing between orifices. An increase in spacing from 2 to 4 times the orifice diameter increased the mixing efficiency significantly. Further increases in spacing did not increase the mixing since the horizontal nonuniformity in the temperature distribution increased as the vertical nonuniformity decreased.

4. For a constant orifice spacing to orifice diameter ratio, S/D, both jet penetration and mixing at any fixed downstream location increased monotonically with increasing orifice diameter. The increase in efficiency is especially significant since it occurs as more mainstream cooling is attempted.

5. For a constant orifice spacing to duct height ratio, S/H, increasing the orifice diameter increased the exit temperature difference ratio consistent with the larger dilution air flow without altering the shape of the distributions. This suggests that for a given momentum flux ratio there exists a value of S/H for which the most efficient mixing is achieved independent of orifice diameter. The orifice size can then be selected to provide the desired jet-to-mainstream mass flow split.

Appendix - Symbols

A_j/A_∞	orifice area to mainstream area ratio, $= (\pi/4)/[(H/D)(S/D)]$
D	orifice diameter; see Fig. 1
E_T	mixing efficiency parameter, see Eq. (2)
H	duct height = 10.16 cm; see Fig. 1
H/D	duct height to orifice diameter ratio
J	momentum flux ratio, $= (\rho_j V_j^2)/(\rho_\infty U_\infty^2)$
S	spacing between centerlines of adjacent orifices; see Fig. 1
S/D	spacing to orifice diameter ratio
S/H	spacing to duct height ratio
T_{EB}	energy balance temperature, $= (\dot{W}_j T_j + \dot{W}_\infty T_\infty)/\dot{W}_T$

T_i temperature at any location in flow field

T_j jet total temperature, = 300 K

T_∞ mainstream total temperature, = 600 K

U_∞ mainstream velocity, = 15 m/sec

V_j jet velocity

W_i mass flow rate at any location in flow field

$\dot{W}_j$ jet mass flow rate

$\dot{W}_j/\dot{W}_\infty$ jet-to-mainstream mass flow ratio

$\dot{W}_T$ total mass flow rate, = $\dot{W}_j + \dot{W}_\infty$

$\dot{W}_\infty$ mainstream mass flow rate

X distance downstream from jet injection location; see Fig. 1

X/H dimensionless downstream distance

Y cross stream distance; see Fig. 1

Y/H dimensionless cross stream distance

Z lateral distance; see Fig. 1

θ dimensionless temperature difference ratio, = $(T_\infty - T_i)/(T_\infty - T_j)$

ρ_j jet density

ρ_∞ mainstream density

References

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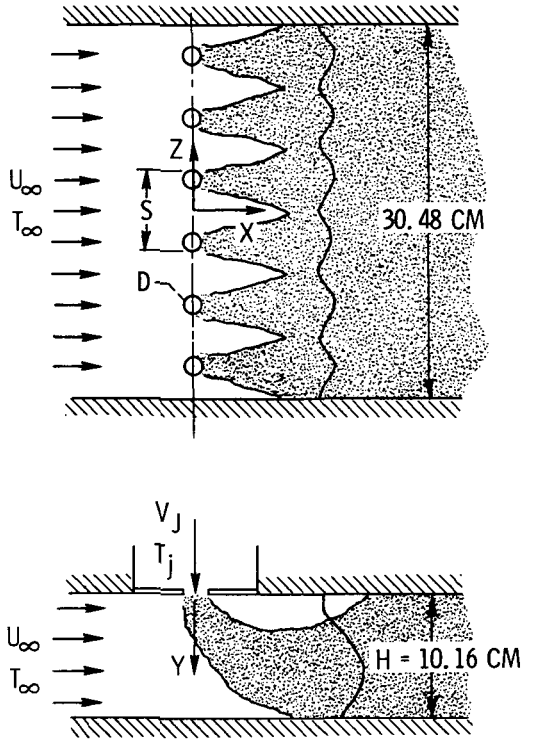

Figure 1. - Schematic of multiple jet flow.

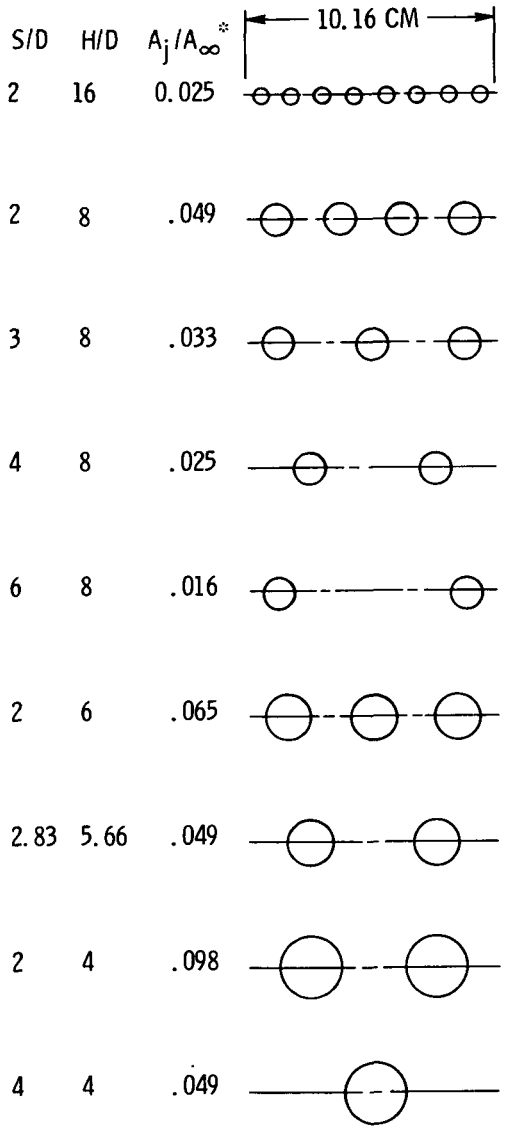

Figure 2. - Orifice plate configurations;
$*A_j/A_\infty = (\pi/4)/(H/D)/(S/D)$

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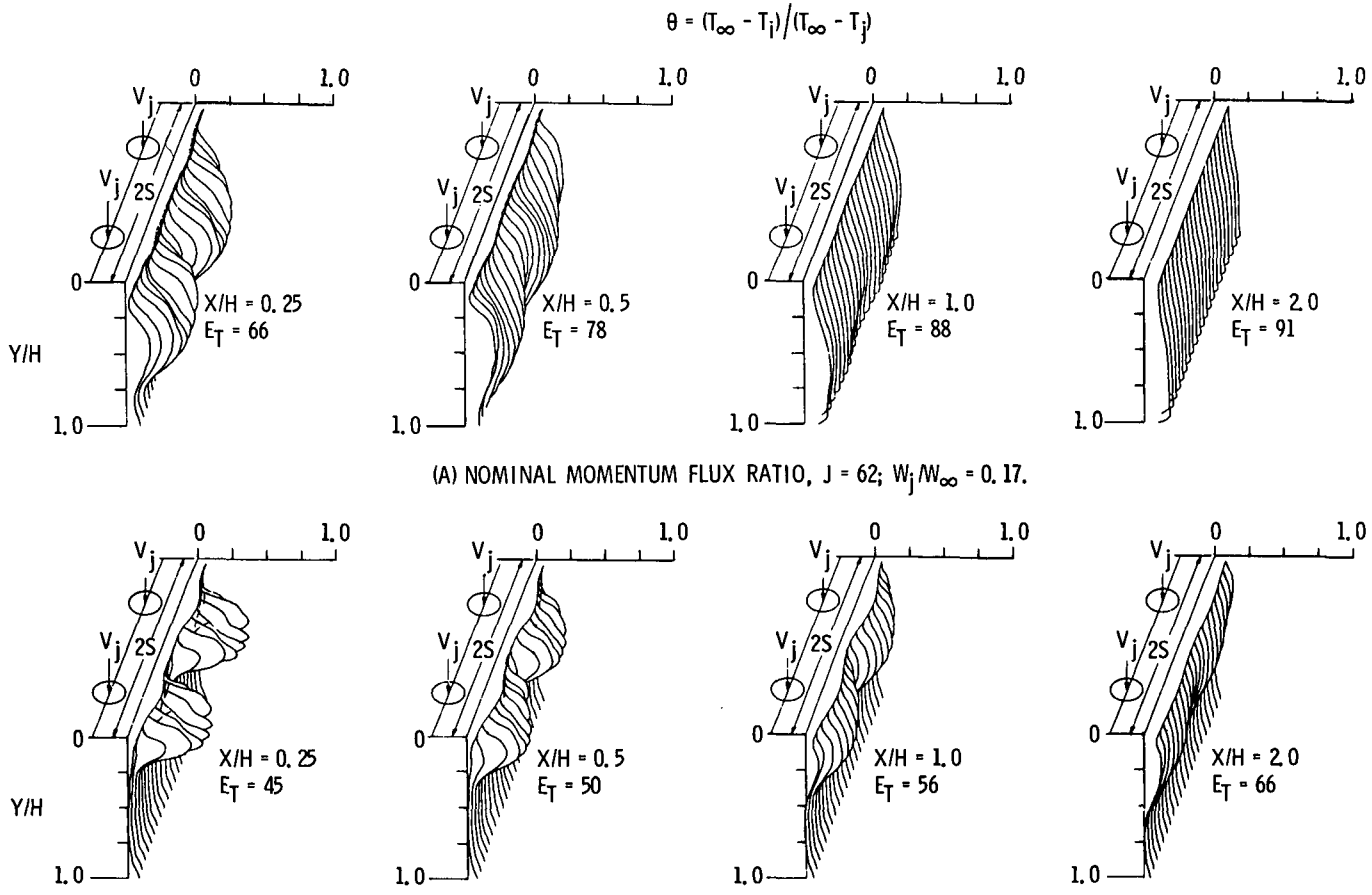
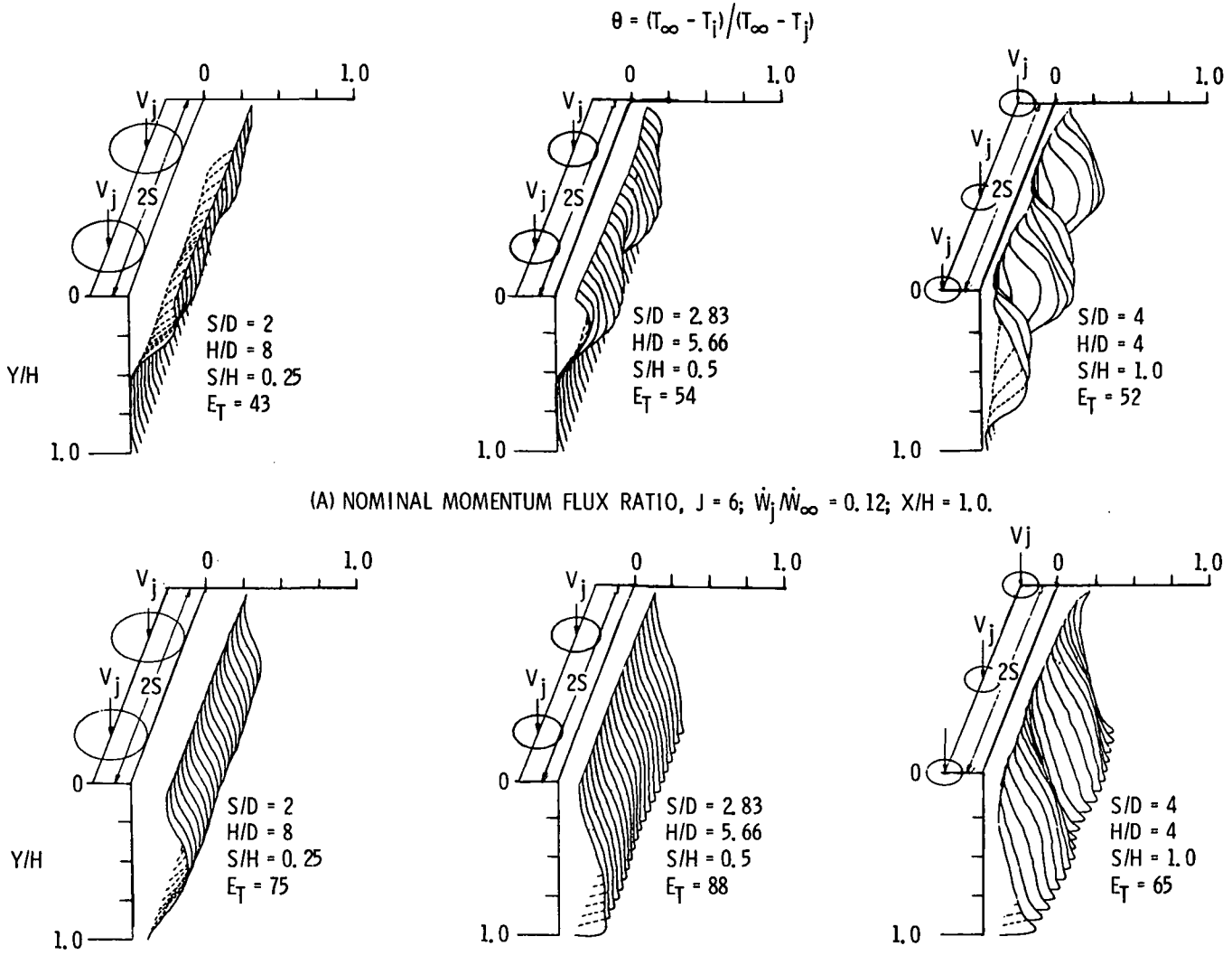


Figure 3. - Effect of momentum flux ratio on temperature profiles; nominal $T_\infty/T_j = 2.0$; orifice configuration: S/D = 4, H/D = 8, S/H = 0.5.



(A) NOMINAL MOMENTUM FLUX RATIO, J = 6; $\dot{W}_j/\dot{W}_\infty$ = 0.12; X/H = 1.0.

(B) NOMINAL MOMENTUM FLUX RATIO, J = 60, $\dot{W}_j/\dot{W}_\infty$ = 0.36; X/H = 1.0.

Figure 4. - Effect of geometric variables on temperature profiles at constant orifice area; A_j/A_∞ = 0.049; nominal T_∞/T_j = 2.0.

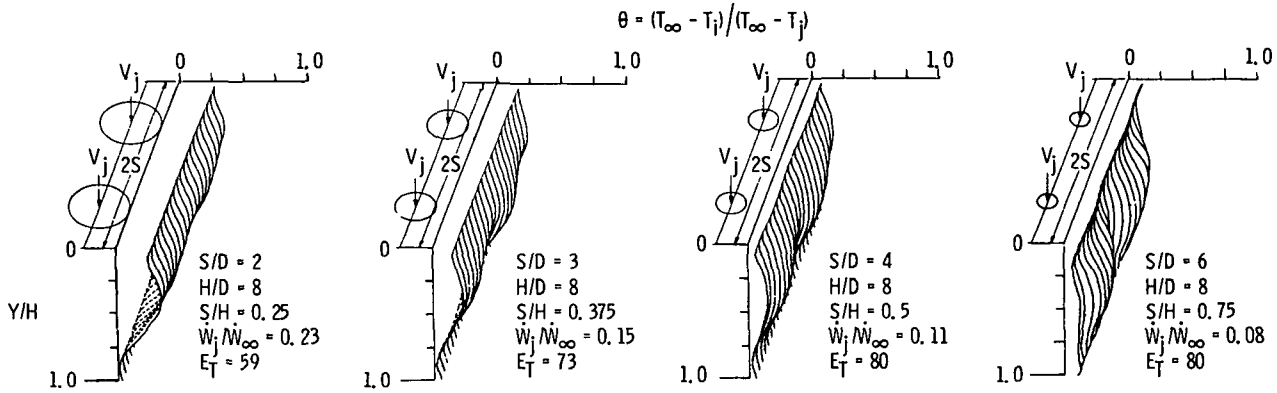


Figure 5. - Effect of spacing on temperature profiles for constant orifice diameter; downstream distance X/H = 1.0; nominal T_∞/T_j = 2.0; nominal J = 25.

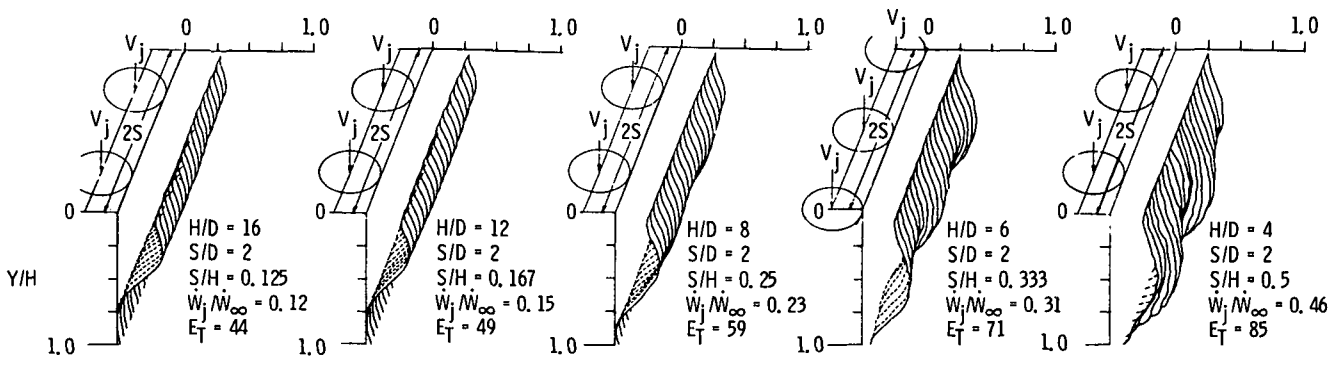


Figure 6. - Effect of orifice diameter on temperature profiles at constant S/D; downstream distance X/H = 1.0; nominal T_∞/T_j = 2.0; nominal J = 25.

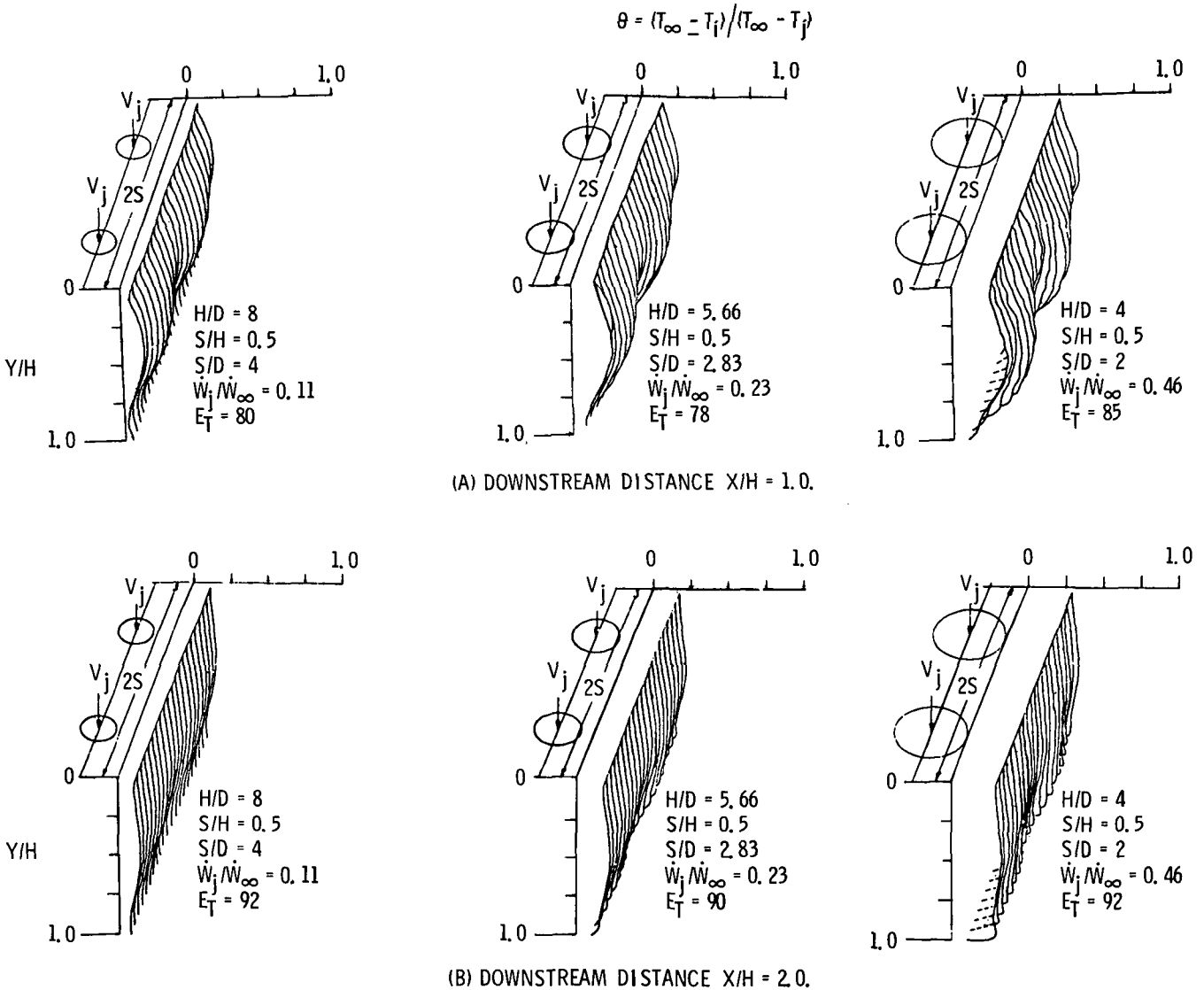


Figure 7. - Effect of orifice diameter on temperature profiles at constant S/H; nominal $T_\infty/T_j = 2.0$; nominal J = 25.

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